



# **Large-scale Simulations and Detailed Flow Field Measurements for Turbomachinery Aeroacoustics**

## **Abstract:**

The presentation is a review of recent work in highly loaded compressors, turbine aeroacoustics and cooling fan noise. The specific topics are: the importance of correct numerical modeling to capture blade row interactions in the Ultra Efficient Engine Technology Proof-of-Concept Compressor, the attenuation of a detonation pressure wave by an aircraft axial turbine stage, current work on noise sources and acoustic attenuation in turbines, and technology development work on cooling fans for spaceflight applications. The topic areas were related to each other by certain themes such as the advantage of an experimentalist's viewpoint when analyzing numerical simulations and the need to improve analysis methods for very large numerical datasets.



# Large-scale Simulations and Detailed Flow Field Measurements for Turbomachinery Aeroacoustics

**Dale Van Zante**  
Acoustics Branch  
NASA Glenn Research Center

**Seminar at The Ohio State University**  
**March 10, 2008**



## Bio:

M.S., 1992, Iowa State University

*“Comparison of Slow and Fast-Response Instrument Flowfield Measurements Downstream of a Transonic Axial-Flow Compressor”*

Ph.D., 1997, Iowa State University

*“Study of a Rotor Wake Recovery Mechanism in a High-Speed Axial Compressor Stage”*

Advisor: Dr. Theodore H. Okiishi

1997-1999, Post-Doc at NASA Glenn

1999-2003, Compressor Branch, NASA Glenn

2003- present, Acoustics Branch, NASA Glenn



I will present highlights from work on several diverse research projects

**Topics:**

- The Proof of Concept Compressor (POCC)
- Constant Volume Combustion Cycle Hybrid Engine
- Engine Turbine Noise Simulation Study
- Cooling Fans: Performance and Acoustic Characteristics



### **Some common themes within the research topics:**

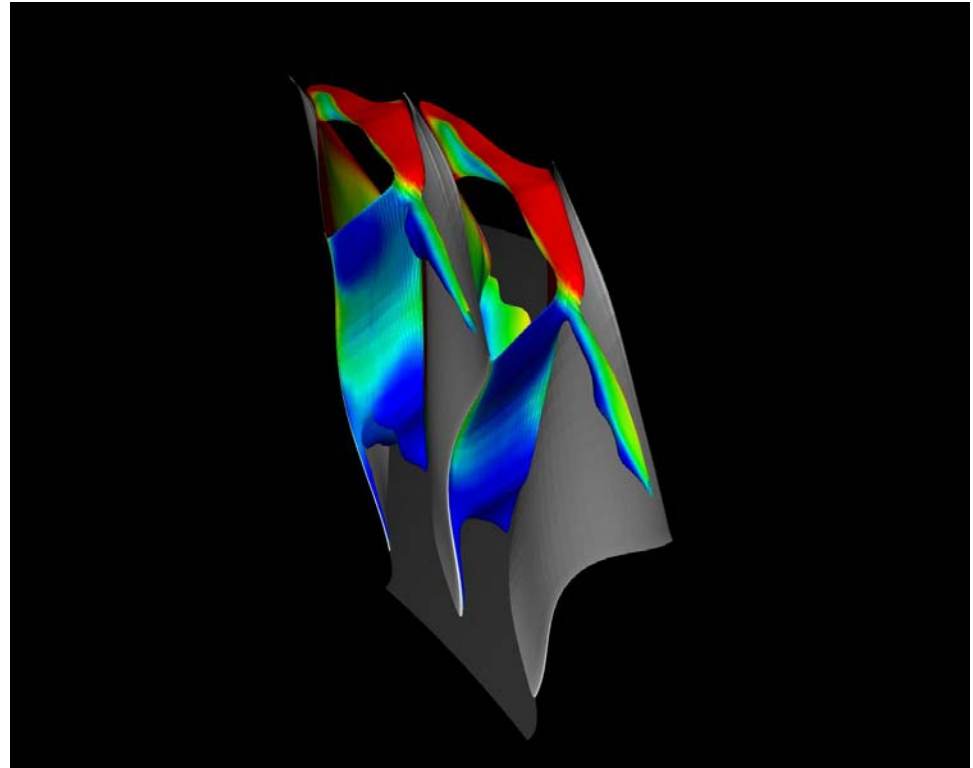
- An experimentalist can run cfd codes! It is useful to take an experimentalist's view when interpreting the data from the simulations.
- Computational resources are so ubiquitous now that numerical simulations are becoming the third pillar of discovery\*.
- Animations of cfd data are more than just pretty pictures.
- Data storage, networking, and analysis methods are not keeping pace with increasing cpu resources. The ability to move, store and analyze the simulation data in reasonable amount of time are sometimes issues.

\* "Petaflop Opportunities for the NASA Fundamental Aeronautics Program," Dimitri J. Mavriplis, David Darmofal, David Keyes, and Mark Turner, 18th AIAA Computational Fluid Dynamics Conference, June 2007.



## The Proof of Concept Compressor Simulation

Where an experimentalist's  
intuition became important





# **The Influence of Compressor Blade Row Interaction on Performance Estimates from Time-Accurate Multi-Stage, Navier-Stokes Calculations**

**Dale Van Zante**

NASA Glenn Research  
Center

**Michael Hathaway**

ARL Vehicle Technology  
Directorate

**Jen-Ping Chen**

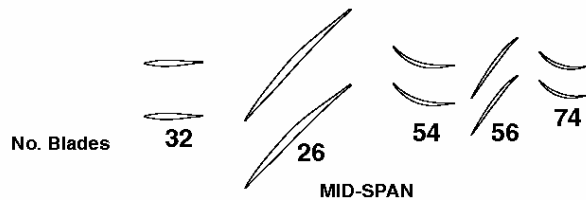
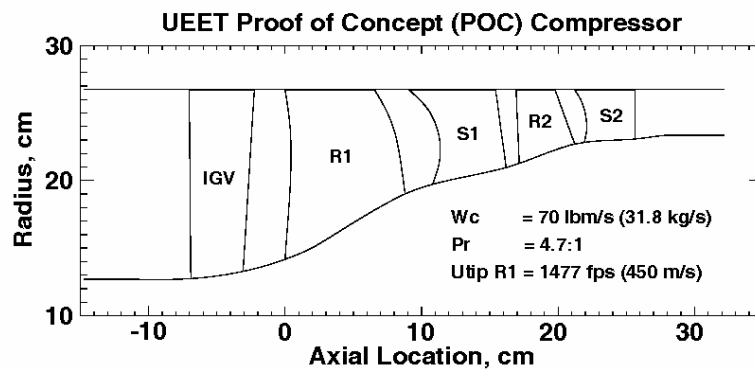
Mississippi State  
University

**Randall Chriss**

NASA Glenn Research  
Center



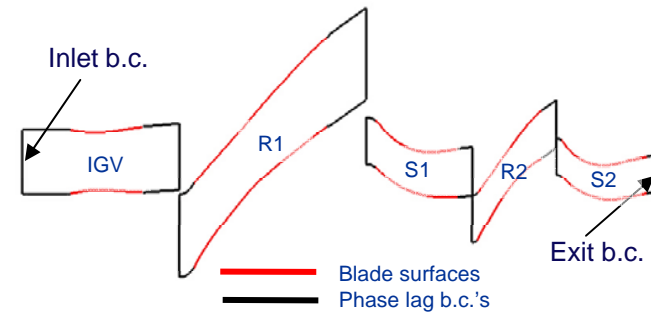
## The three modeling techniques



Animations of data from the phase-lag simulation showed anomalous behavior. This led to an in depth look at the interactions occurring within the compressor.

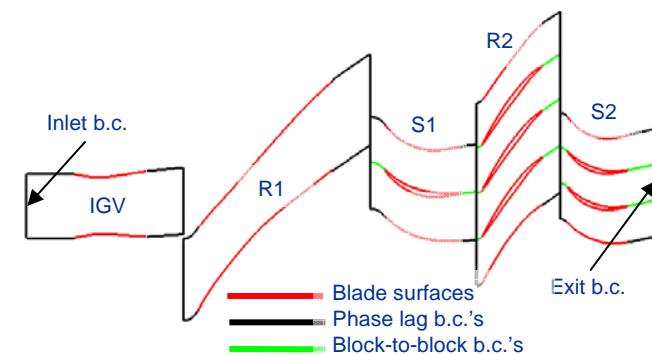
### Case 1: Single-passage phase-lag

-> standard approach



### Case 2: Multi-passage phase-lag

-> increased circumferential domain



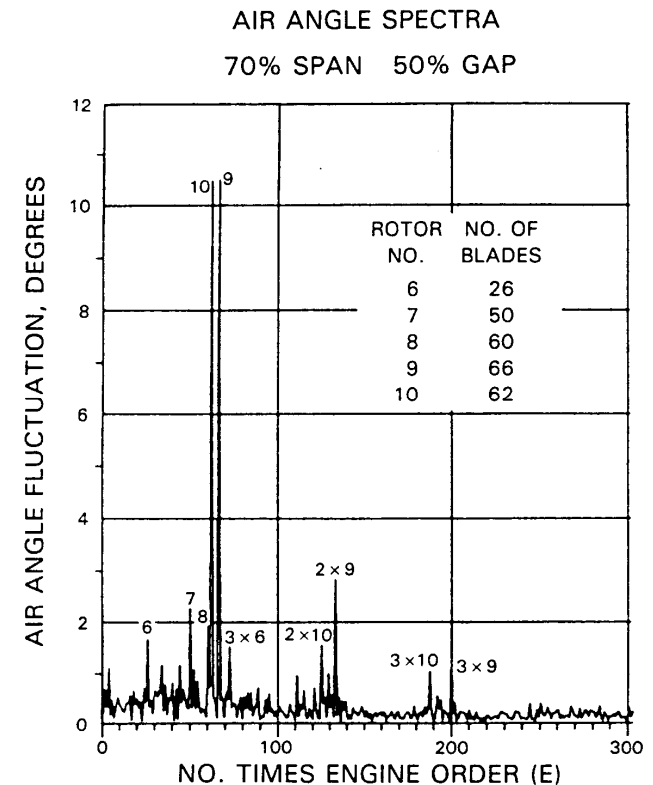
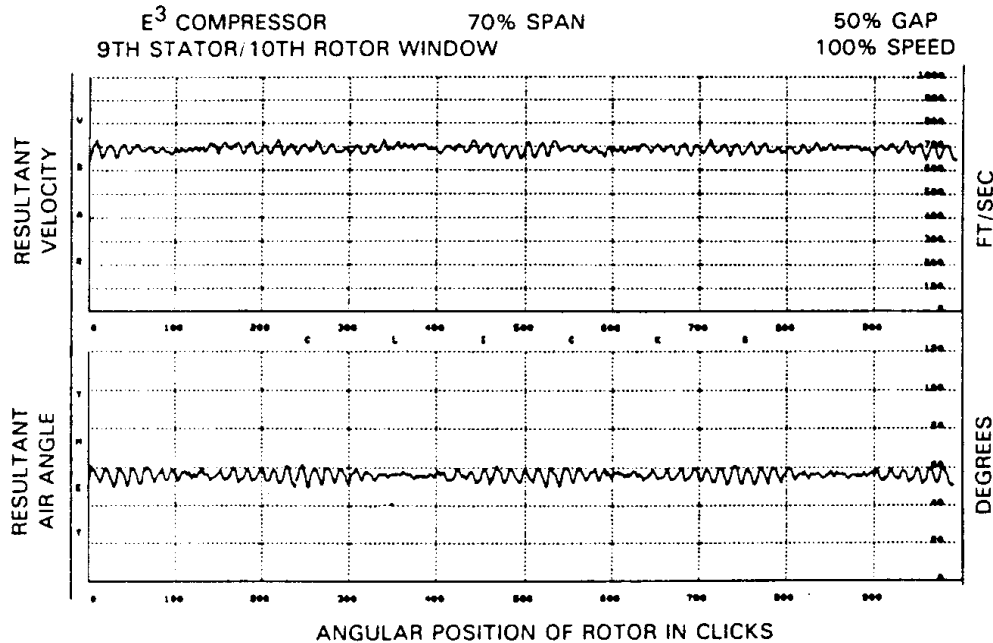
### Case 3: 1/2 annulus, periodic

-> the least modeling assumptions





## Previous example of a rotor-rotor interaction



From: Williams, M.C., "Inter and Intrablade Row Laser Velocimetry Studies of Gas Turbine Compressor Flows," Journal of Turbomachinery, July 1988.

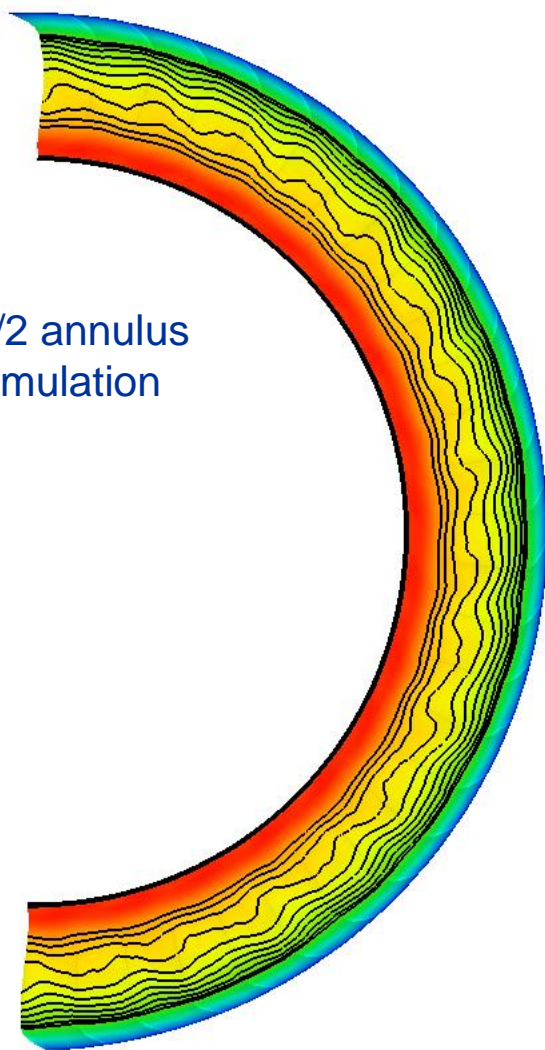
The 4E beat pattern in the data is a result of rotor 9 - rotor 10 interaction. The blade counts of the rotors differ by 4.

Also see: He, et al., "Analysis of Rotor-Rotor and Stator-Stator Interferences in Multi-Stage Turbomachines," Journal of Turbomachinery, October 2002.

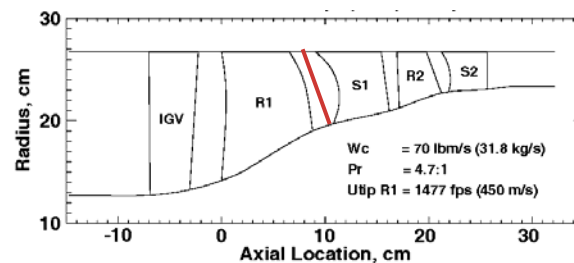
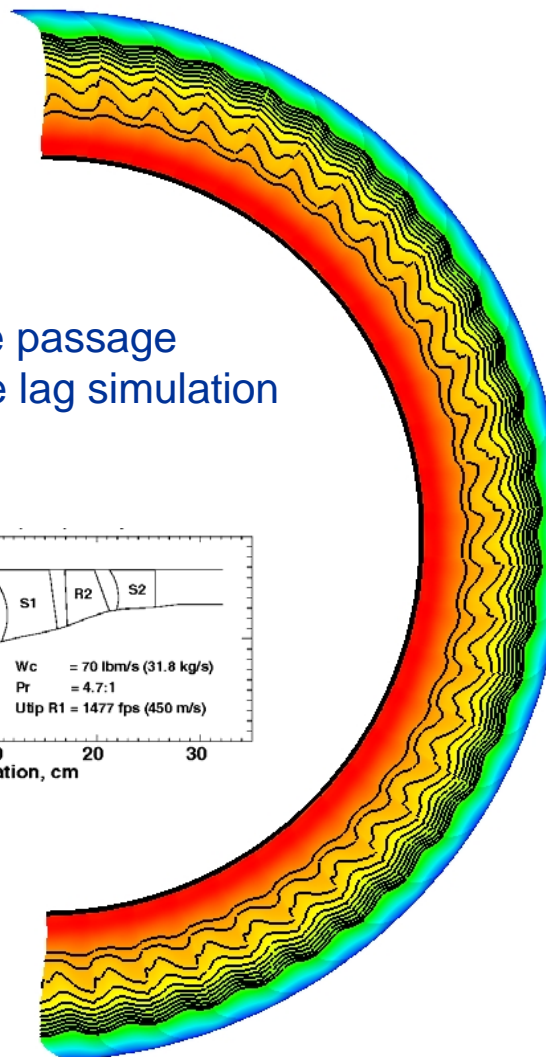


## The time-average, stator 1 inlet plane adiabatic efficiency

1/2 annulus  
simulation



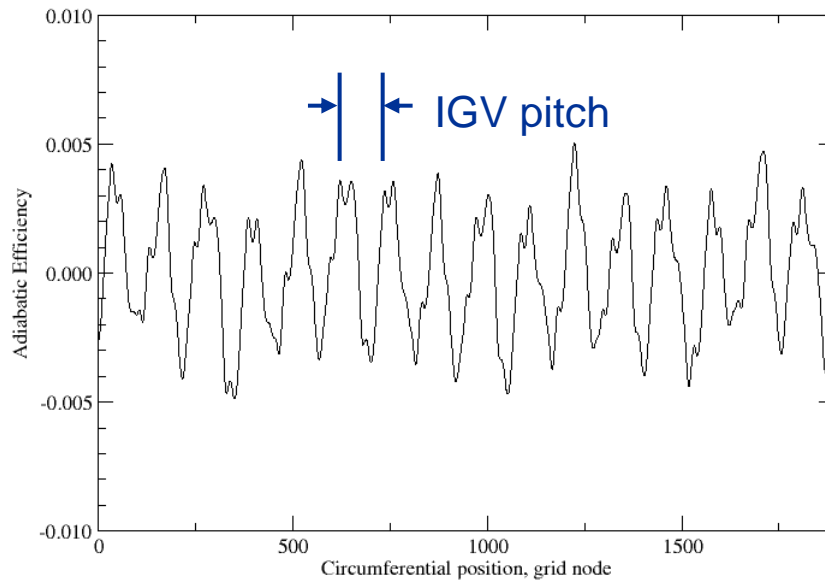
Single passage  
Phase lag simulation



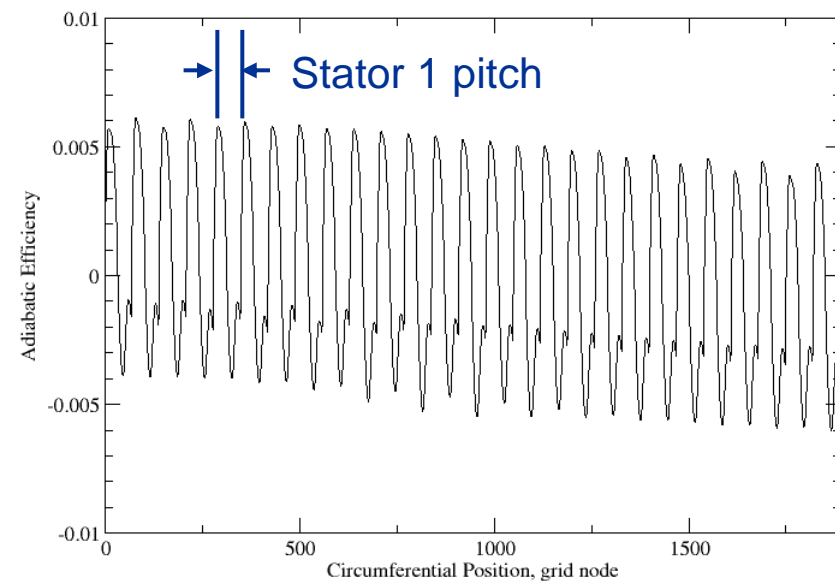


## Adiabatic efficiency at 50% span, stator 1 inlet plane

1/2 annulus periodic simulation



Single passage phase lag simulation



- The 1/2 annulus simulation contains variations at the IGV pitch spacing in addition to other mode content.
- The phase lag simulation contains predominantly stator 1 pitch content with little evidence of the expected IGV mode content.



## Conclusions

- The periodic sector simulation converges in nearly an order of magnitude fewer iterations than simulations which incorporated phase-lag boundary conditions. The periodic simulation is then competitive with the phase-lag simulations when considered on a combined resource-time basis.
- Rotor-rotor and stator-stator interactions lead to circumferential variations of properties which are stationary in the reference frame of the blade row. Simulations using the phase-lag boundary condition were not able to completely capture this effect resulting in subtle and cumulative changes in performance through the machine.

This paper is published in the January 2008 ASME Journal of Turbomachinery.



# THE ATTENUATION OF A DETONATION WAVE BY AN AIRCRAFT ENGINE AXIAL TURBINE STAGE

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Additional acknowledgments to:  
Matt Ellis, Purdue University  
Timothy McKnight, University of Cincinnati



## Objectives

The NASA Constant Volume Combustion Cycle Engine Technology (CVCCET) project analyzed the feasibility of using a detonative combustor in a conventional turbofan engine.

### **Primary:**

- determine the attenuation of a pressure pulse by an aircraft engine axial turbine

### **Secondary:**

- estimate the turbine aeroperformance
- evaluate the possibility of aeroelastic issues with the turbine

## Approach

Use the TURBO code to simulate a notional PDE/turbine interaction. TURBO allowed the detonation tube to be coupled directly to the turbomachinery. Time histories of static pressure through an axial turbine stage were saved along with 3D flow fields at selected time steps for the attenuation and performance analysis respectively.



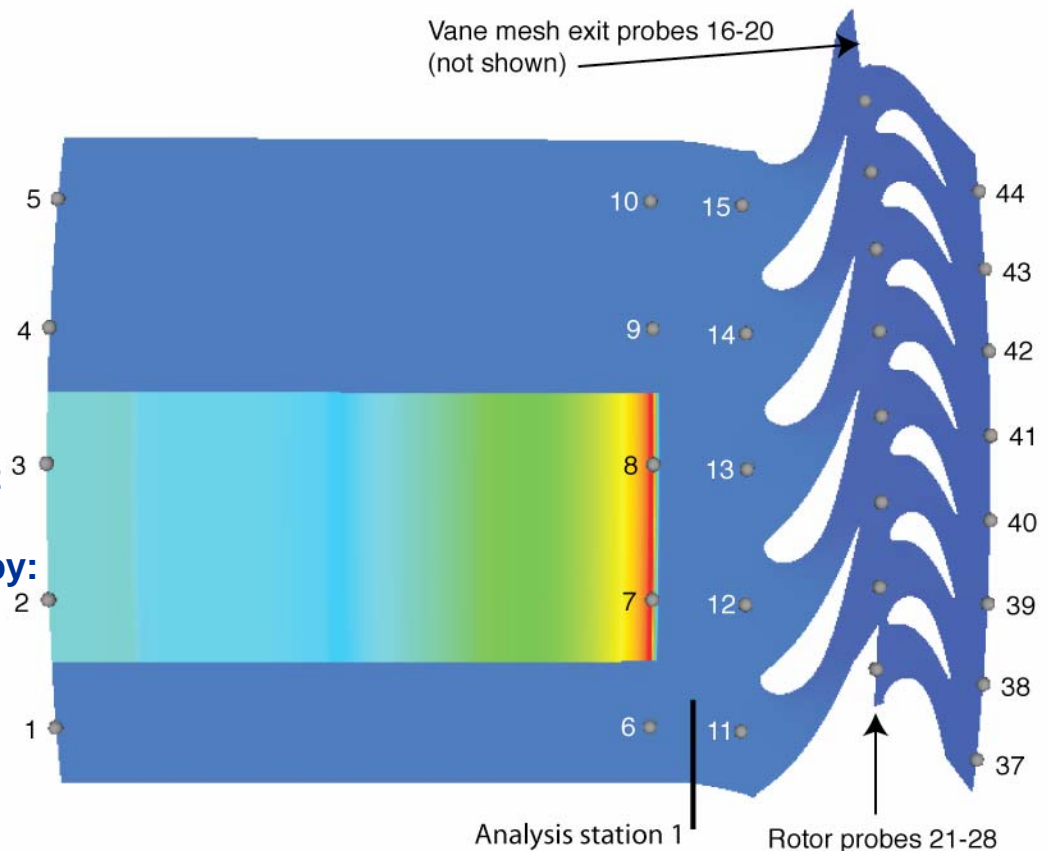
# Initial Condition

- the detonation tube is modeled as an initial value problem with conditions from Dan Paxson
- tube firing rate is assumed to be 80Hz [every 2 turbine rotor revolutions]
- inlet boundary: specified  $T_t$  and  $P_t$

The goal was to match the 'average' tube exit conditions to the turbine design inlet condition.

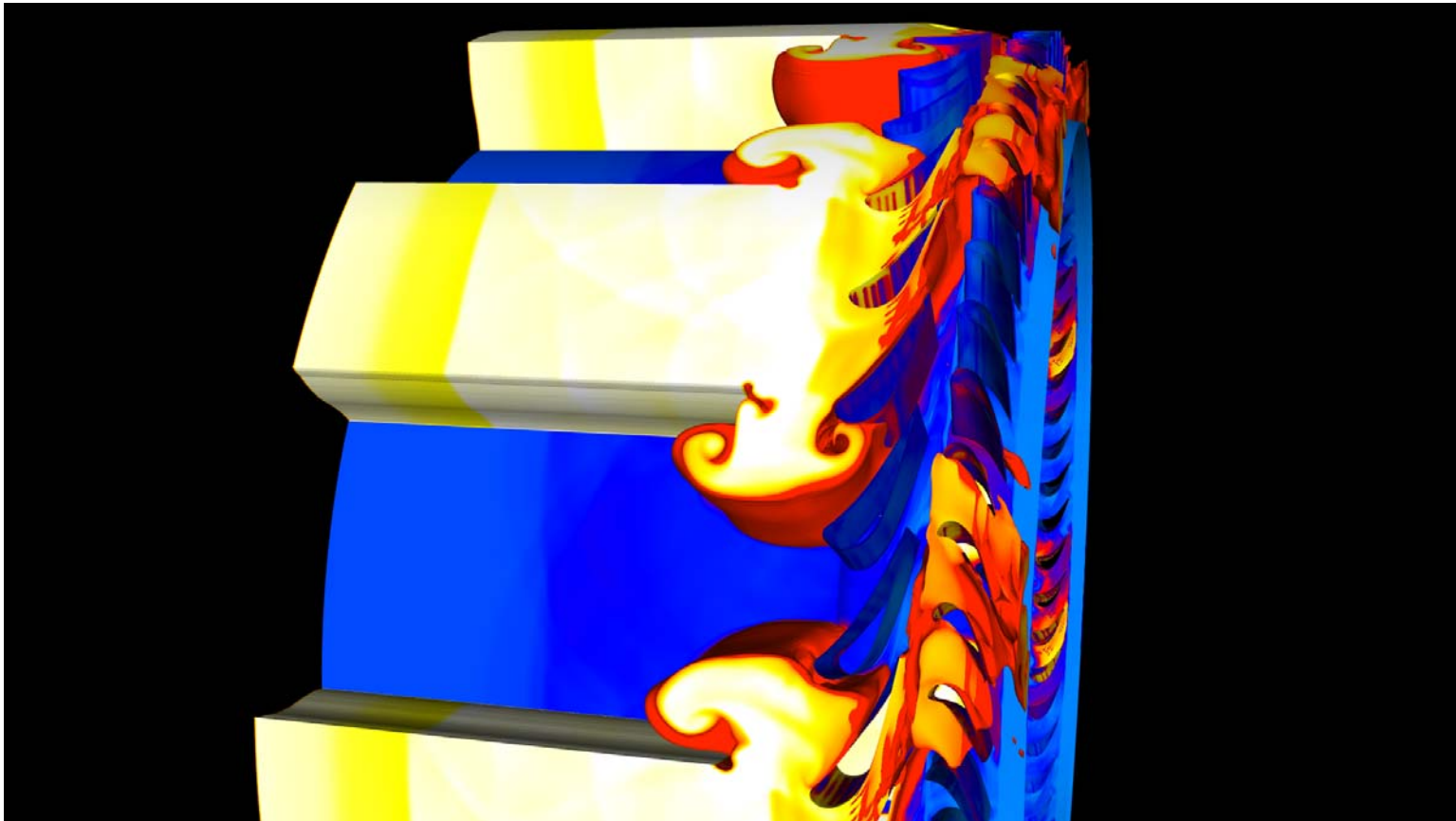
The turbine inlet condition is controlled by:

1. The tube firing frequency
2. The choice of inlet total pressure and total temperature
3. The detonation tube exit area



Numbered dots are numerical pressure probe locations. Averaging for performance analysis was done at Analysis Station 1, the rotor/stator interface, and the rotor exit.





Movie





## Why is it useful to animate data from the simulations?

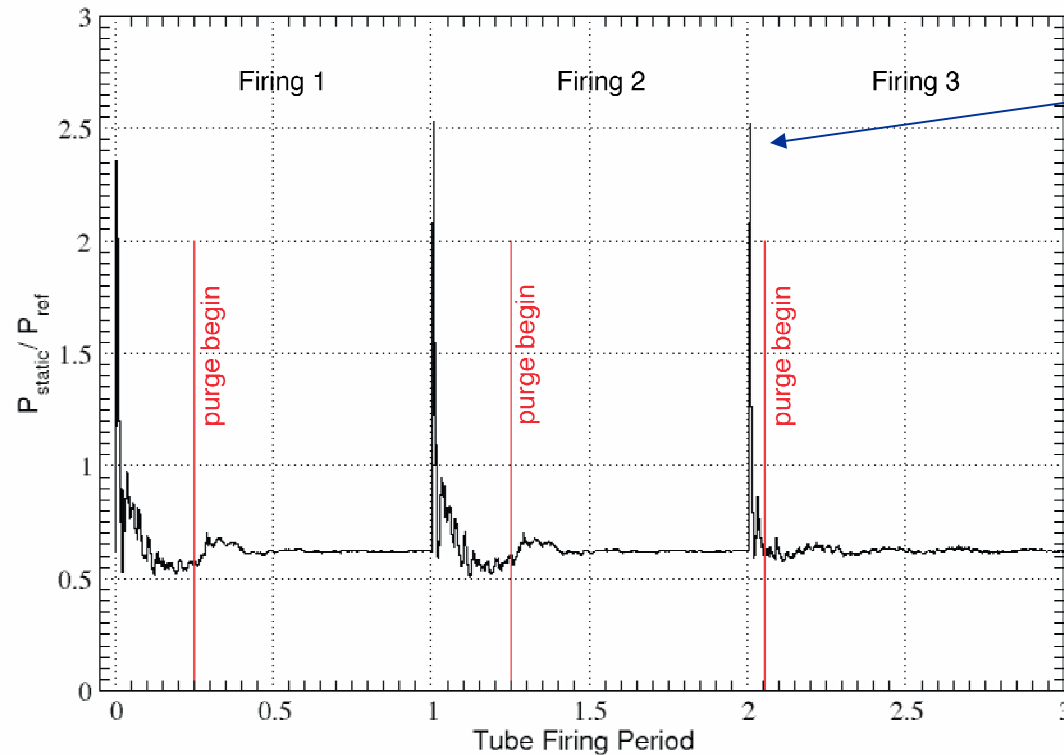
- For the POCC simulations, limitations of the modeling approach showed as 'glitches' in the animations.
- For the CVCC simulations, the root cause of 'anomalies' in the numerical pressure probe data were obvious. More next...

## How is it possible to animate very large datasets?

- high-capacity, high-speed file systems
- distributed analysis and rendering
- with the help of Jay Horowitz from the Glenn ACCL, the time to generate the animation went from >1hr to minutes using Enight DR
- the CVCC dataset was only 8M nodes, what I will show in the turbine noise discussion is 10-20x larger so the data handling and visualization issues only get worse



## Time history of Probe 12

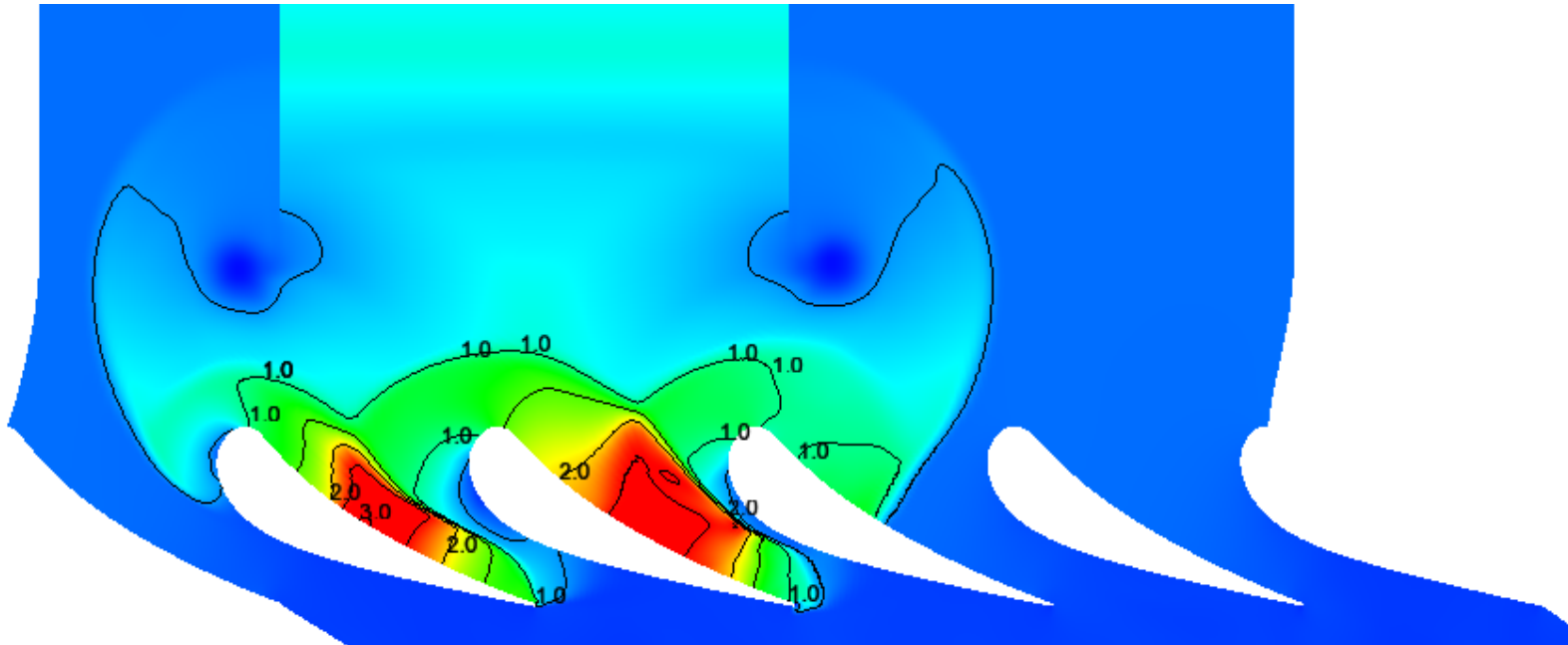


A double peak appears with the shock, with the second peak higher than the first. Why?

Data from all three firings are used in the attenuation analysis.  
Flow field data from Firing 3 only are used in the performance analysis. (Note that the turbine is off-design.)



## Shock focusing



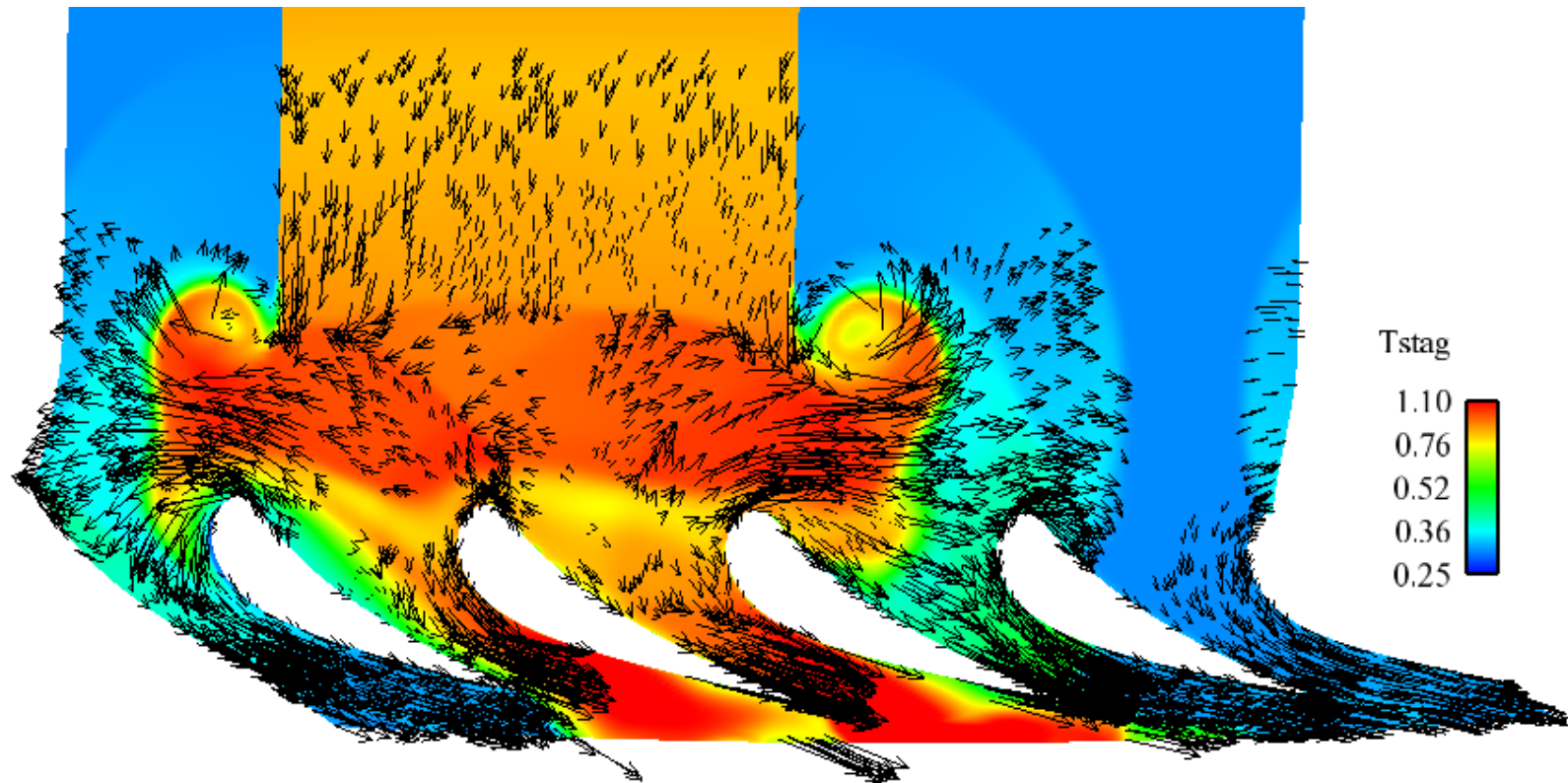
The pressure surface of the vane focuses the shock and pressures ~100 atm are produced, albeit for a very brief time.

"Response of Turbine Rotor Blades Downstream of a Pulse Detonation Combustor"

M.A. Bakhle, J.B. Min, and T.S.R. Reddy



## Turbine Flow Capacity



The vane passages directly downstream of the tube choke and cause the jet of hot fluid to spread circumferentially.



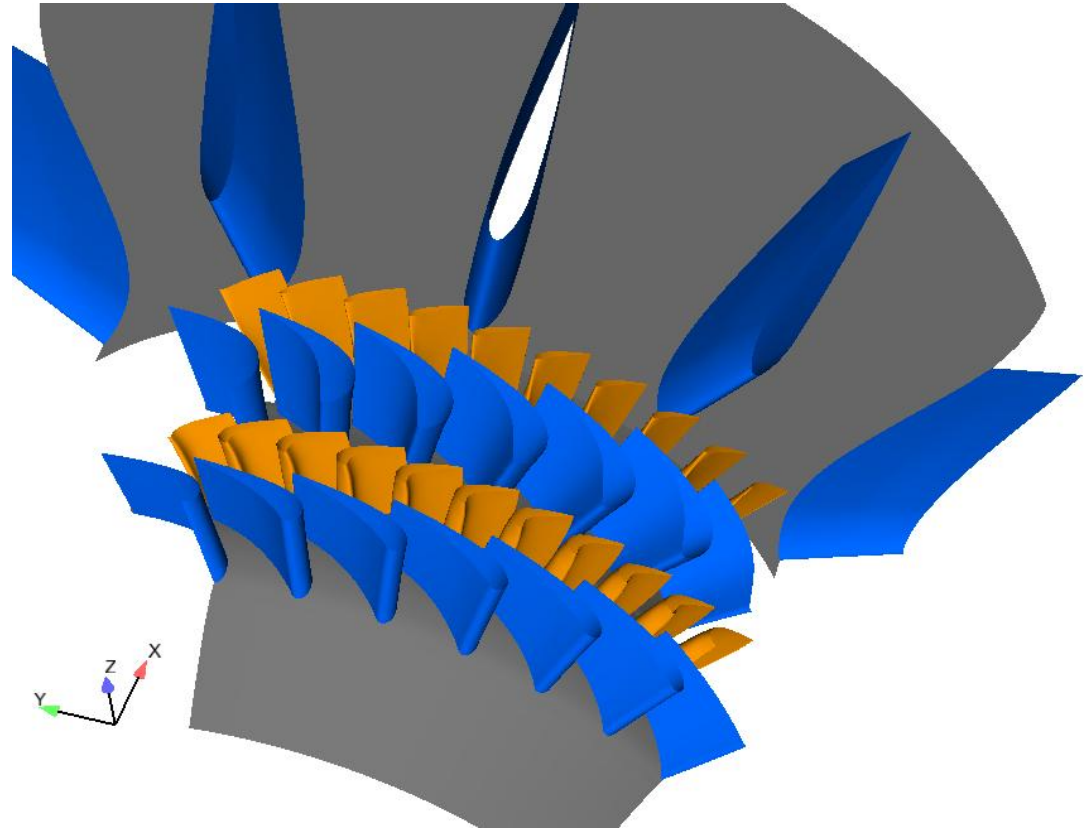
## Conclusions

A time accurate RANS simulation of a notional detonation tube coupled to a HP turbine stage was analyzed for pressure wave attenuation and turbine stage aeroperformance.

- The pressure wave attenuation across the turbine stage is such that with a sufficient number of turbine stages, the pulse detonation combustor noise would be manageable in the overall noise signature of the engine.
- The aeroperformance of the turbine stage is poor due to an insufficient enthalpy rise across the pulse detonation combustor. A fair assessment of the turbines' ability to utilize the unsteady flow is not possible without better matching the combustor and turbine.



## Engine Turbine Noise Simulation Study





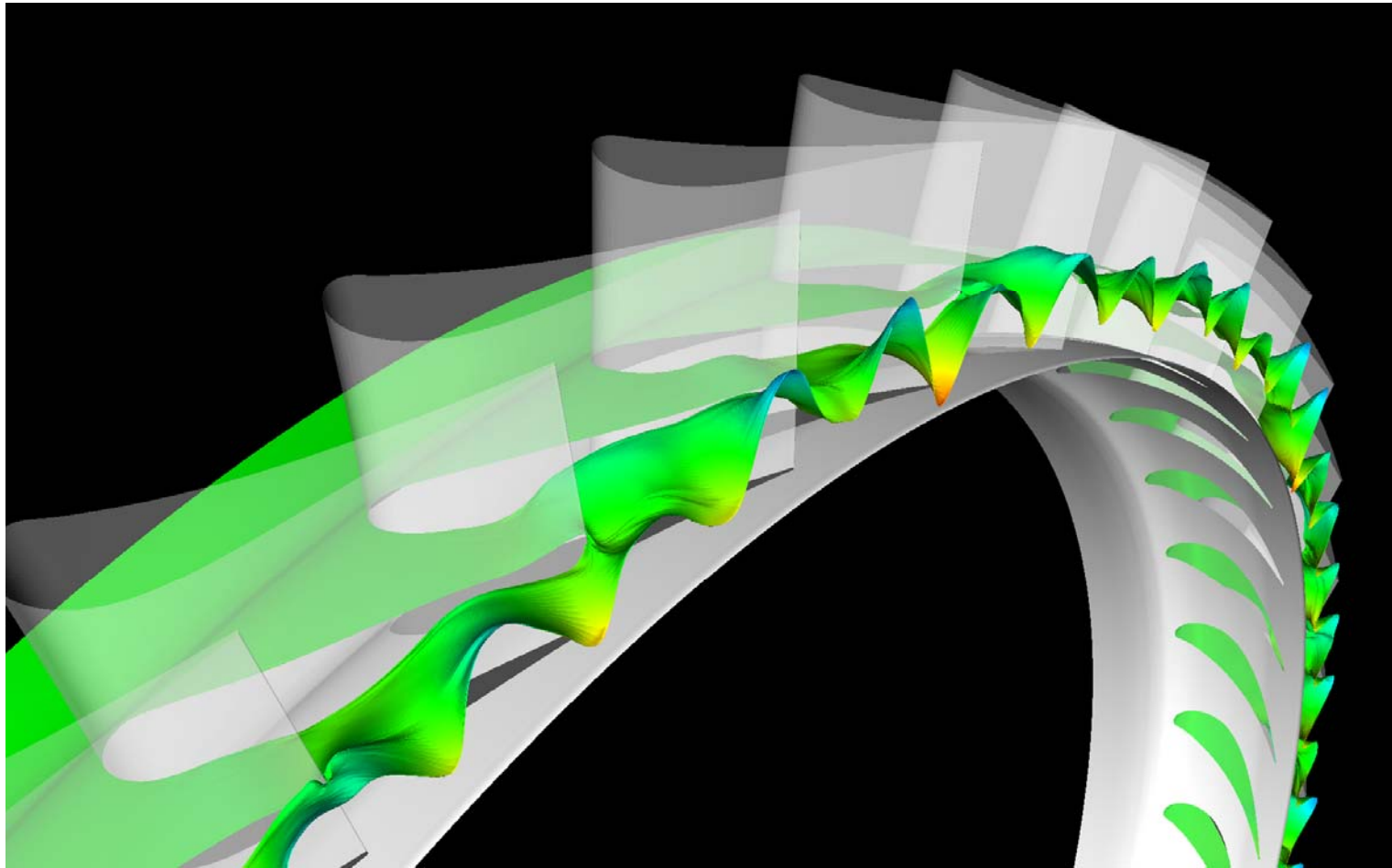
As the noise produced by the fan and jet exhaust of high-bypass engines is reduced, other sources of engine noise, such as the turbine, become significant.

Sources of turbine noise:

- blade-row viscous interaction
- potential field interaction
- entropic

Simulations and analysis of 3 cases are currently underway using the TURBO solver:

1. HPT stage 1 with a coarse mesh (8M nodes)
2. HPT stage 1 with a fine mesh (80M nodes), resolve to 2BPF
3. Entire HPT+strut with a fine mesh (165M nodes), resolve to 2BPF



Movie





## Turbine Noise Study Status

Cases 2 and 3 are currently running on the new Aeronautics supercomputer, RTJones.

RTJones is an SGI ICE system with 4096 cpus  
It is available to support NRA efforts as well

There is also an effort to add an unsteady inlet condition to TURBO so that combustor outflow fluctuations can be imposed on the turbine inlet.



## Cooling Fans: Performance and Acoustic Characteristics



A representative axial fan which was tested for its aeroperformance and acoustic characteristics.



# **An assessment of NASA Glenn's aeroacoustic experimental and predictive capabilities for installed cooling fans Part 1: Aerodynamic performance**

**Dale E. Van Zante  
L. Danielle Koch  
Mark P. Wernet  
Gary G. Podboy**

**NASA Glenn Research Center  
Cleveland, OH**

**Internoise 2006, Honolulu, Hawaii**



**GE90 turbofan engine for the Boeing 777**



**Objective:** to determine if aircraft engine design and analysis techniques for performance and low noise are applicable to cooling fans

Aircraft engine fan design goals:

- efficiency
- durability
- low noise
- reduced cost

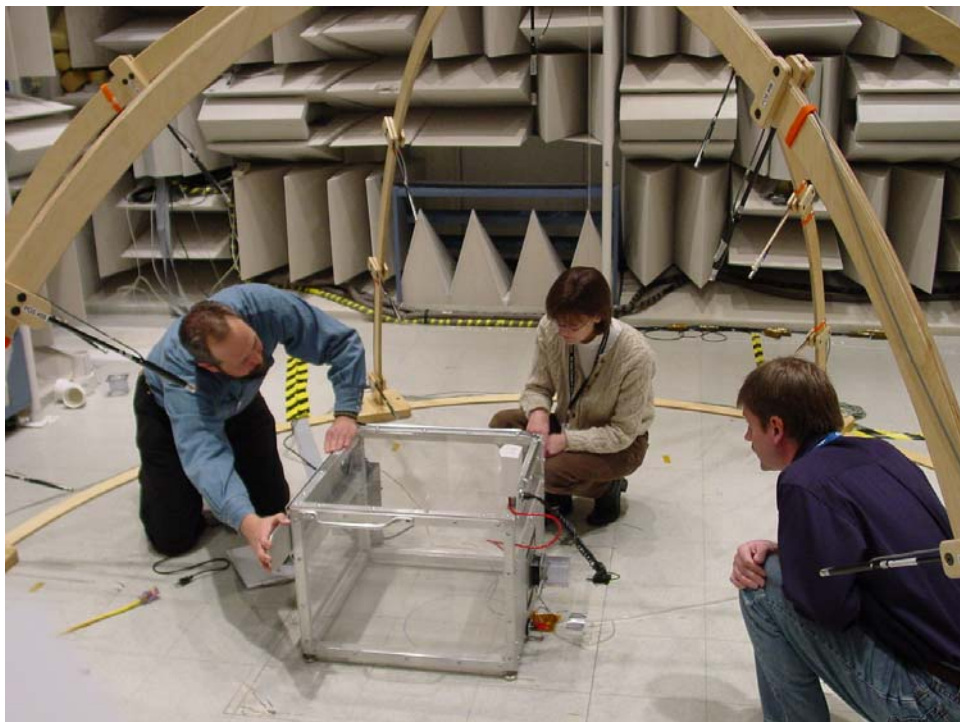
The technological evolution of aircraft engine fans is driven by the use of 3D computational methods and experimental measurements.

What is the design maturity of cooling fans relative to aircraft engine fans?



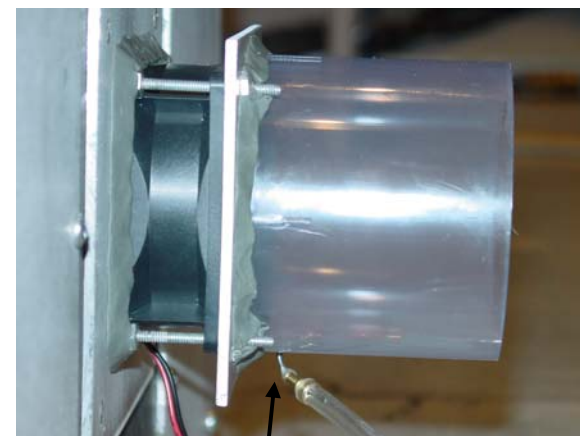
Rolls-Royce Trent 1000 fan for the A380





Testing the fan on the automated plenum in the Glenn Acoustic Testing Laboratory (ATL)

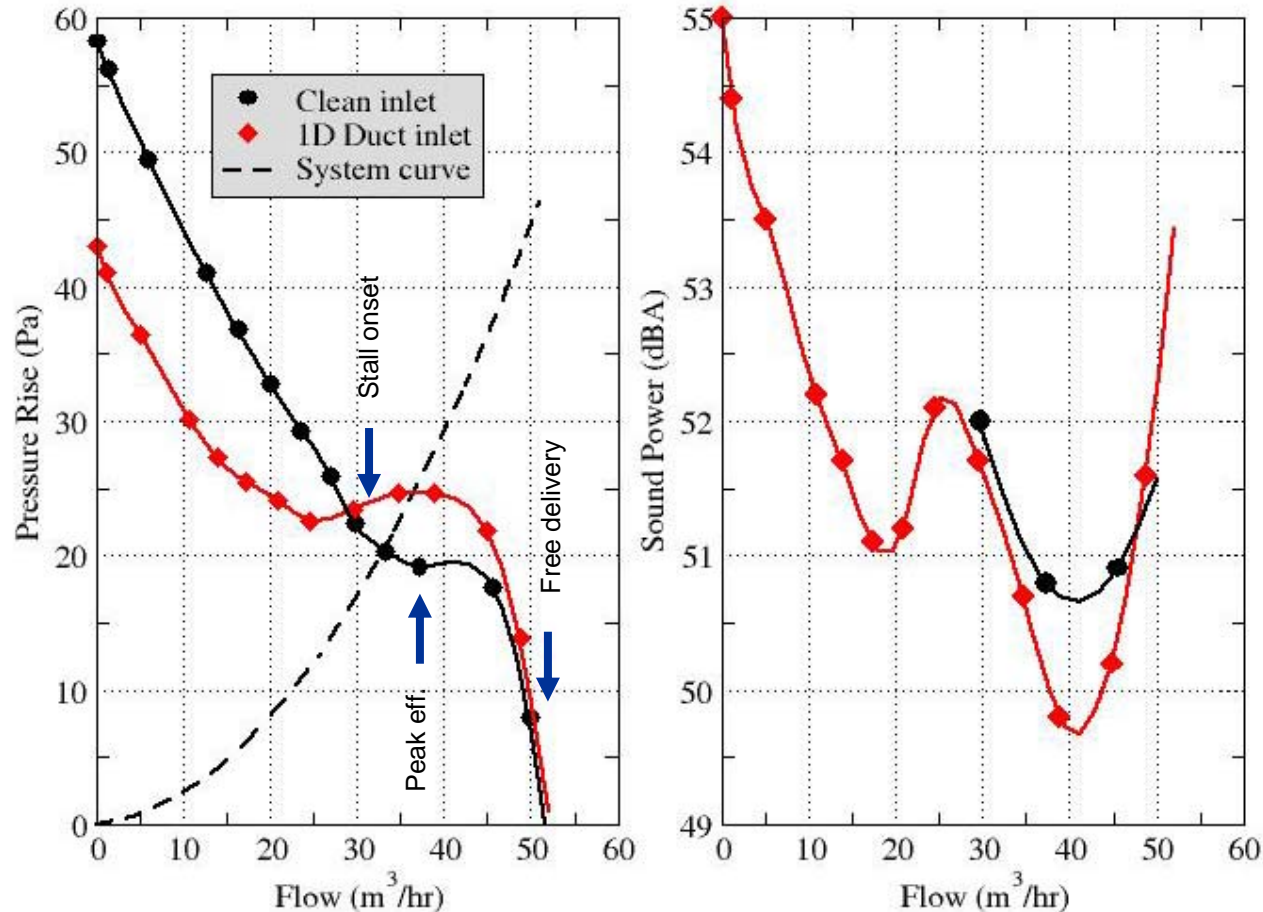
The fan was tested with and without an inlet duct. The duct contained a wall static tap to determine the fan inlet pressure.



Wall static tap



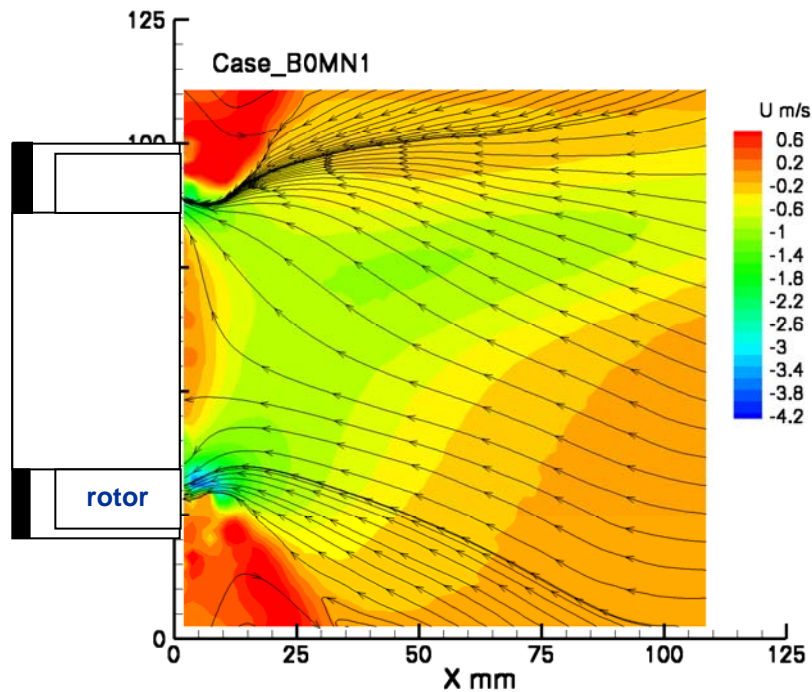
## Cooling fan pressure rise and sound power characteristics



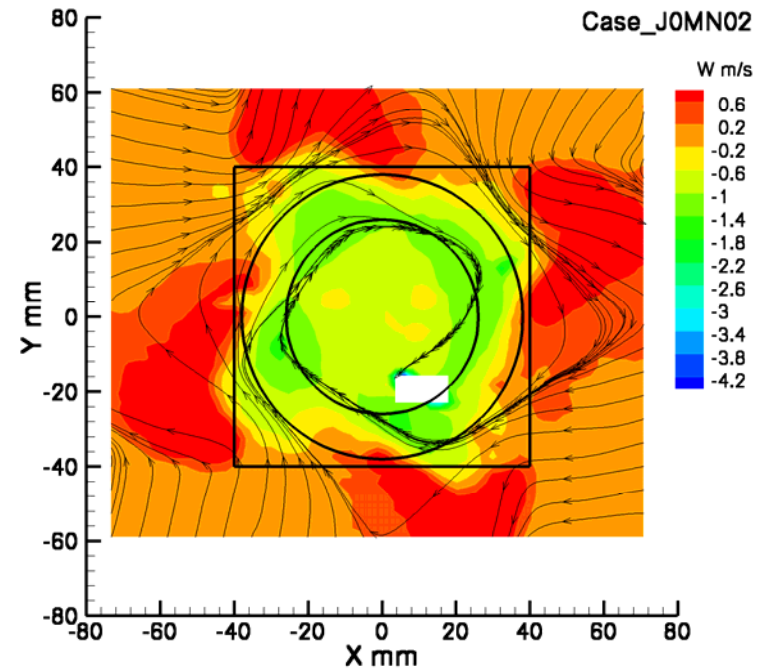
- the inlet duct increased pressure rise and decreased sound power at the fan peak efficiency operating point
- detailed fan flowfield measurements will help explain the performance increase and will also show how the fan flowfield deteriorates at stall onset



What happens if the fan is mismatched to the system and operates in mild stall?



Meridional view, 2D PIV, mild stall.



Fan inlet, 3D PIV, mild stall.

Swirling flow comes OUT of the inlet (red regions in above images) and leaks preferentially at the partial bellmouth cutouts.

Air that the fan is meant to exhaust is recirculated instead.

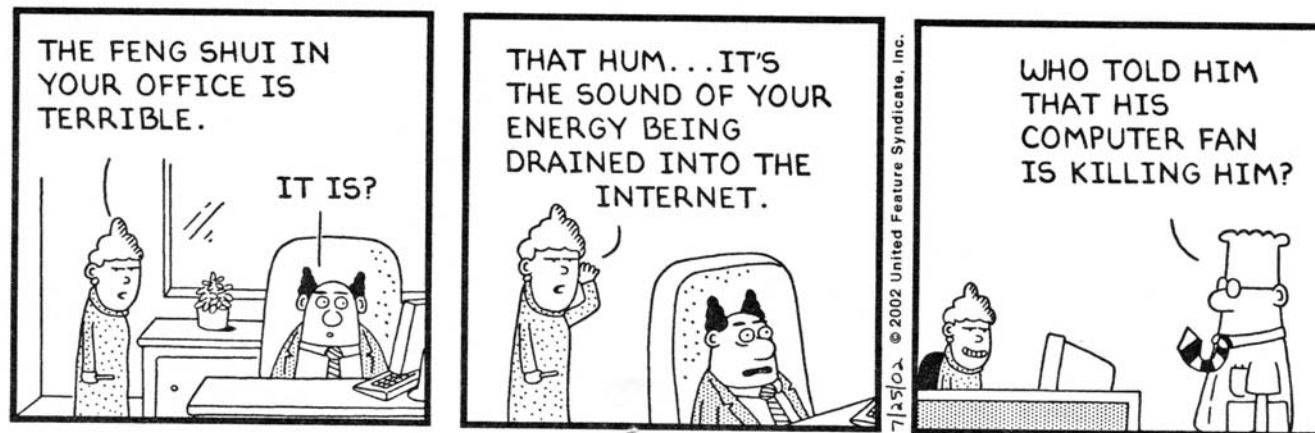


## Cooling Fan Summary

We feel that there are significant gains to be made in cooling fan aero design and installation.

There are some fan manufacturers taking advantage of aircraft engine design tools. The aero performance of these fans is impressive. We would like to investigate the acoustic characteristics of these new fan designs.

<http://www.grc.nasa.gov/WWW/Acoustics/collaboration/focusonfans.htm>







## The Closing

Over the past 5 years I have worked on several diverse research projects.

The success of these projects is due in part to:

1. A blend of experiments and computations mixed with a healthy skepticism of the results from both.
2. The use of existing computational tools and high-performance computing resources for exploration of important issues in turbomachinery fluid mechanics.
3. A vision of what to look for in the simulations along with assistance from the GRC GVIS staff to make it happen.